ENGINEERING The Air-Conditioned Greenhouse

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AGRICULTURE can be defined as the controlled growing of plants, and therefore it is of paramount importance to know the principles of plant growth and the conditions under which this growth takes place. The Plant Physiology Department of the California Institute of Technology is especially equipped to study both these sides of the problem of plant growth. Others have described the basic contributions made by investigators of the problem of internal chemical control of growth. In this work a very close cooperation between botanists and chemists has brought significant results in the field of biological chemistry.

Another approach to the plant growth problem has been carried out at the Institute to the present advanced stage through the use of the air-conditioned greenhouses built in 1939. This approach is a study of the climatic requirements of plants. Such a study requires complete control over the environment of the plant. This environment can be divided into two parts: 1) the soil in which the roots grow, and 2) the air. The soil is an incredibly complex system, which fortunately we can replace by a well-aerated solution of the inorganic salts necessary for plant growth. With such a simplified root medium, much information concerning plant nutrition has been obtained.

LIGHT VERSUS AIR

But there are no substitutes for air and light in growing the above-ground parts of a plant. The difficulty in controlling this air lies mainly in the need for high light intensities to make plants grow normally. In general, plants require intensities as high as or not less than 1/10 sunlight. Such intensities can be reproduced with difficulty by artificial light sources. But whichever the light source, intense light causes strong heating. This throws off the temperature control of the surrounding air, so that in experiments usually either the temperature of the air around the plants is controlled at a low light intensity, or the plants receive full light at uncontrolled temperature.

To achieve air temperature control at high light intensities it is necessary to install an air-conditioning system differing in many respects from the principles established for human comfort air-conditioning.

The first deviation is obvious: a much larger volume of air has to be passed through the greenhouses to counteract the temperature increase due to light absorption. Depending on how close a temperature control is desired, the air-conditioning system has to renew the air one to four times per minute in the greenhouse. This requires both heavy blowers and wide air ducts. Although such a requirement seems obvious, in many systems which were installed in greenhouses between the years 1926 and 1940 the ducts were entirely insufficient to deliver the volume of air needed to maintain temperatures reasonably close to the setting of the thermostat. This experience led to a wide-spread belief that greenhouses could not be air-conditioned.

The second deviation lies in the air distribution. To move such a large volume of air through a greenhouse without strong air currents and without channelling, it must be introduced from many points and through many openings. The air must move past the surfaces absorbing the light to carry away the heat and the water vapor produced. This means that in a greenhouse the air must move past all leaves. When the plants in a greenhouse are all of the same size, this can be accomplished by providing horizontal currents just over the plants, and having an adequate air supply from below. The heated air will then be carried off as it rises in the horizontal sheet of moving air.

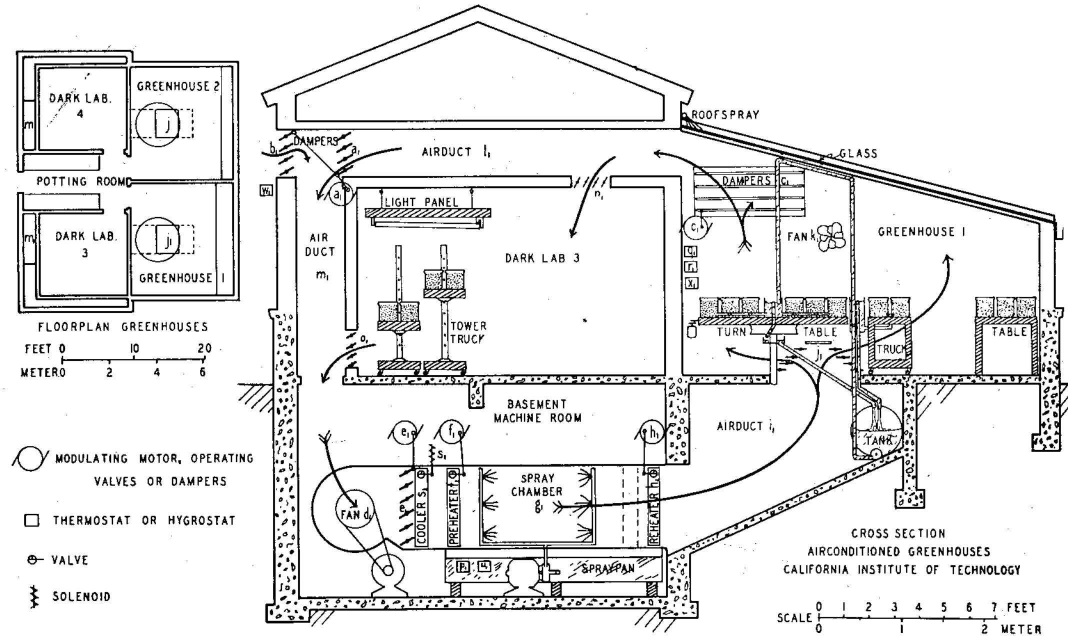
THE WORKING MODEL

In the present air-conditioned greenhouses, plants of different sizes are being and will have to be grown; hence the system of a horizontal sheet of moving air is not very good.

A number of tests have been carried out with different methods of introducing air into greenhouses. For this purpose a model was built of sufficient size to measure air currents around plants of the size used in most experiments. A blower delivered 600 ft^3/min to a plenum under the greenhouse floor. The floor consisted of wooden slats of four in. width, which could be spaced according to need, to let the air pass between them. It was found that if the air was injected through slits of 1/3 in. between the boards, it mixed with the room air almost immediately, and then rose at a rate of about 20 ft/min evenly upward, unimpeded by three ft tall tomato plants, growing in four in. pots, four per square foot. There was

The air-conditioned greenhouses at the California Institute. The sloping glass roof towards the left covers the greenhouses, the tile roof covers the adjoining darkrooms.

Floor plan of the present greenhouses (left side faces north) and cross median section through house "1" and room "3".



little tendency for the air to move sideways towards the exhaust slits before it had reached the ceiling. It was found essential to have the air in the plenum back up against a dead air-space before rising through the slits in the floor.

Another requirement in order to obtain good air distribution with this system is large exhaust openings and wide exhaust ducts. For the main air resistance must be located in the floor slits, when an evenly rising mass of air is desired.

The air-distribution thus obtained in greenhouses is ideal for experimental purposes, where plants are grown in individual containers, but the vertically rising air cannot be used in greenhouses where continuous bench space is required.

If we ask now what the first small air-conditioned greenhouses built in 1939 have contributed to botanical knowledge, an amazing story can be told.

EXPERIMENTATION IN THE AIR-CONDITIONED GREENHOUSES

Whereas usually any first new machine or apparatus has to be rebuilt and improved before it is generally useful, the foresight and care in planning of the present air-conditioned greenhouses made them eminently useful, even though many improvements can be suggested now as a result of eight years of experimentation in these houses.

The primary achievement is reproducibility of experiments with full grown plants. Tomatoes, tobacco and many other plants receive even in winter in Pasadena enough light for optimal growth, and therefore their development is controlled by factors other than light. These other factors, especially temperature, can be controlled, and therefore the whole development of the tomato plant is under control. In this way comparable tomato plants can be grown at any time of the year, so that experiments can be run throughout the year without interruption during summer or winter. The difference between such standardized plants and tomato plants grown in an ordinary greenhouse has become very apparent in our recent experiments with sugar application to plants. Whereas tomatoes grown in ordinary greenhouses sometimes grow better, and sometimes poorer, after being sprayed with a sugar solution, plants grown under rigidly controlled conditions responded in the same way when they had been subjected to the same conditions. This fact is really self-evident as a necessary corollary of the causality principle. The amazing thing is that research workers with plants had so long been satisfied with lack of reproducibility in their experiments.

The second achievement of the air-conditioned greenhouses is theoretically far more important. By disassociating the various climatic factors influencing the development of the plants, the exact role of each factor by itself can be assessed.

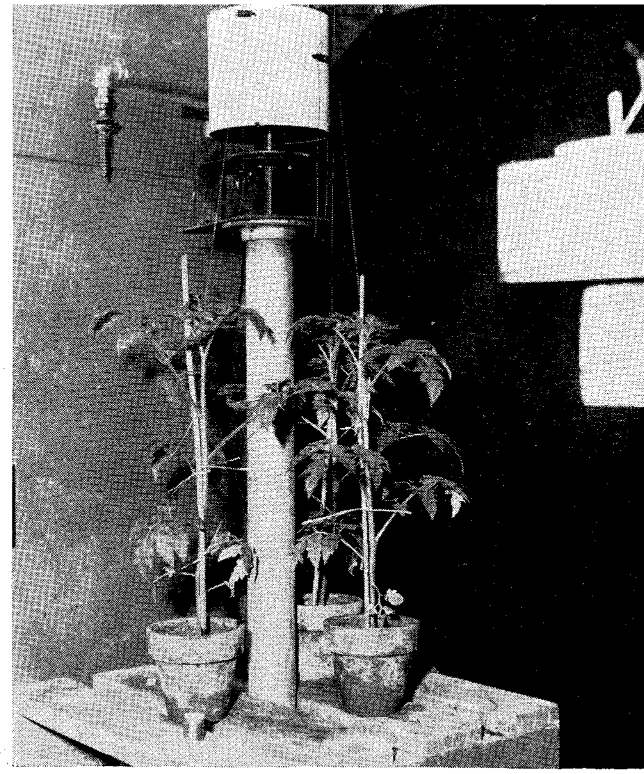
In field experiments stronger light is associated with higher temperature and lower humidity, so that the effects of each factor by itself cannot be deduced from experiments. Separating temperature, humidity and light, it was discovered that the night conditions determine whether a tomato or pepper plant sets fruit. It also seems that the old saying that corn needs very warm nights for best growth is not entirely correct. It needs warm days and fairly cool nights. The beneficial effect of the warm day may overshadow the less favorable effect of a hot night. Thus it becomes possible to assess accurately the effect of individual factors and their interaction for each plant variety. In this way it becomes possible to choose the proper climatic data for judging the fitness of a local climate for the growing of a particular plant or crop.

The study of the interaction between the environmental factors makes this work of particular value for agriculture. If, for instance, it is stated that the optimal night temperature for tomatoes in 65°F, this holds only for a certain variety when the plants have reached a certain size and for a certain light intensity. Therefore in the field we have to know all qualifications before we can apply knowledge gained in the laboratory. A complete set of air-conditioned rooms and greenhouses can supply this information necessary for aplication in the field. This will make plant physiological knowledge much more useful for agriculture.

The accurate and complete knowledge of the reaction of plants to the individual components of the climate will gain special significance in connection with long-range weather forecasting. Then the farmer can plant the varieties of annual crop plants which will respond best to the climate to be expected in any growing season. In this development meteorologists and plant physiologists will have to work in close association, the latter determining which factors are of most significance for particular crops, and the meteorologist making the forecasts for such particular factors.

Perhaps the most important function of the air-conditioned greenhouses is that they furnish the physical conditions to study specific processes in plants, such as water uptake, water loss, transport of water, salts and sugar, hormone production, synthesis of organic components, etc. Many of these processes

Recording the growth of tomato plants. A silk thread is attached to the tip of the plant, runs over a small pulley, and at its other other end carries a pen. This marks a drum, which turns at the rate of one revolution every eight days. The setup is mounted on a truck, which can be moved to different conditions, so that growth can be recorded under different day and night temperatures, in light or darkness.

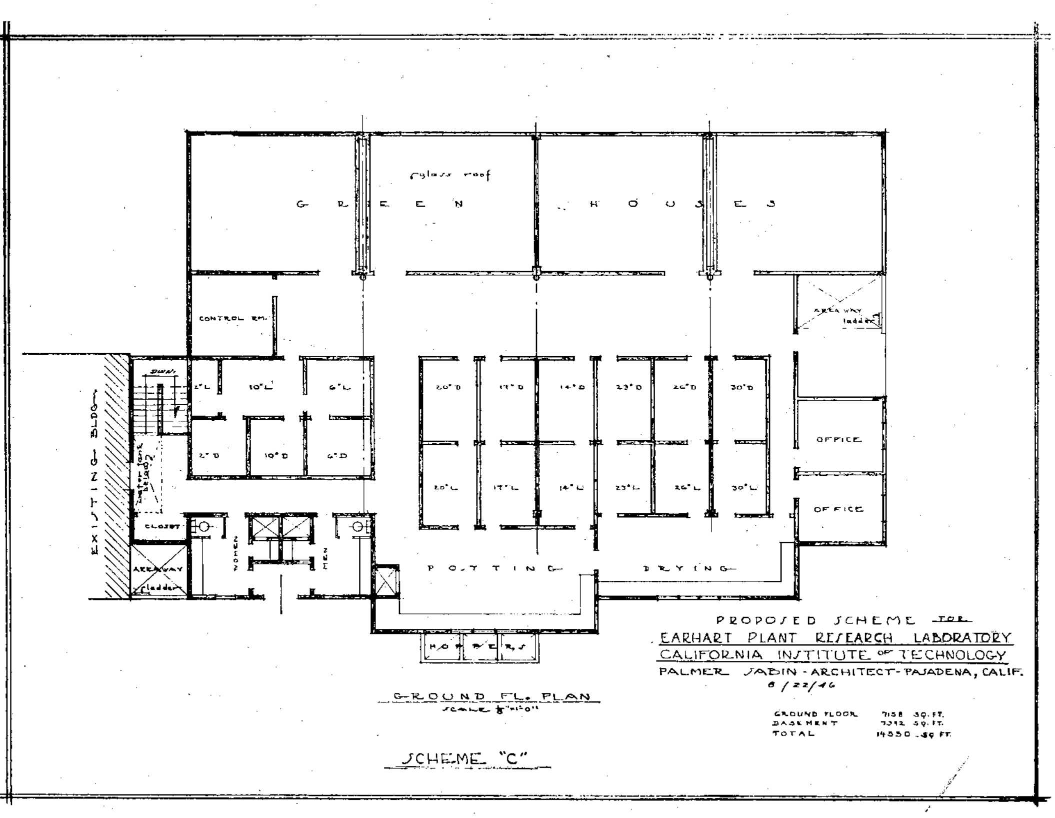


are only slightly known, because most experiments on them have been carried out under uncontrolled or inadequate conditions. With the physical set-up of air-conditioned greenhouses, and the presence of so many eminent physicists and chemists, it is possible to probe much deeper into problems concerning plants. It is very likely that this work will give a powerful stimulus to making Botany a science as exact as Physics and Chemistry are at present.

Considering the very poorly defined and practically uncontrolled conditions under which plants have been generally grown, it is not surprising that physicists especially were reluctant to assist botanists in solving the physical problems connected with the life activities of plants. Now that we are able to work under strictly defined conditions, it must be possible for botanists and physicists to attack problems of hormone, food and water movement, etc., jointly. Thus the greater accuracy obtained not only improves the research but will tend to expand it into the borderfield between Botany and Physics, a practically virgin field.

The present air-conditioned greenhouses were built as an experiment, but they have long since passed the experimental stage. They are now an absolute necessity for further plant physiological work, just as much as the thermostat and pH meter have become essential for physico-chemical work. However, the limit of what can be accomplished in the present air-conditioned greenhouses has been reached. Space limitation and the limited number of different conditions make it impossible to expand the work now being carried out; such expansion is essential, however, if the results are to be applicable in agricultural work.

These considerations led the Earhart Foundation to make a gift to the Institute, enabling it to construct a complete set of air-conditioned greenhouses, darkrooms and artificial light rooms, which will cover practically the whole range of climates on earth. If the present air-conditioned greenhouses have already been so productive, it can be conjectured how important the projected greenhouses will be for the advancement of the Botanical Sciences and of Agriculture. And with these new Earhart Greenhouses, botanical work at the California Institute of Technology can be expected to yield the utmost in results. It is hoped that many guests will come to avail themselves of these facilities, thus making them useful far beyond the boundaries of our own interests and establishing the Earhart Greenhouses as a center of botanical research.



Floor plan of the projected Earhart Plant Research Laboratories at the Institute. Illustrated is the arrangement around a central hallway of four separate greenhouses and 18 light and dark rooms for controlled temperatures ranging from 2° to 30°C.

A number of service rooms, such as the potting room, drying and harvesting room, and control room are on the same floor: a shop, laboratory, more offices and more controlled temperature rooms are projected in the basement, together with the air-conditioning equipment. The entrance of the building is through the washrooms, which act as a quarantine station to prevent as much as possible the introduction of pests and diseases. To the south the new building is connected with the present air-conditioned greenhouses.